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# Acoustic Reflectivity of Nets: Implications Concerning Incidental Take of Dolphins

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## ABSTRACT

Sonar target strength measurements of several types of nets and associated gear were made using simulated dolphin echolocation signals. The different types of nets included; a) standard commercial monofilament gillnet used in the salmon mothership fishery, b) prototype hollow core mo nofilament net, c) Macah tribal cord setnet, and d) multifilament nets. Target strength measurements were made at four angles of incidence, $0^{\circ}$ (normal to net), $15^{\circ}$, $30^{\circ}$, and $45^{\circ}$. The standard gillnet had the smallest target strength which was relatively independent of the angle of incidence. The target strength based on the peak-to-peak values of the echoes varied from -59 to -62 dB. Using echo energy within the integration time of *Tursiops truncatus*, the target strength was found to be between -54 and -59 dB. Biosonar detection ranges for different sea state conditions were estimated using the noise-limited form of the sonar equation and target detection data obtained for *Tursiops truncatus* in Kaneohe Bay, Oahu, Hawaii. The results suggest that an echolocating dolphin should be able to detect a gillnet at ranges long enough to avoid entanglement, even in sea state 6 conditions. Several possibilities for the seeming inability of dolphins to detect gillnets are discussed.



**KEY WORDS:** Acoustic reflectivity of nets. Incidental take of dolphins by gillnets. Dolphin sonar detection of nets.

# I. INTRODUCTION

Coastal and high seas gillnet fisheries results in the incidental take of large numbers of small cetaceans annually world wide. Dall's porpoise (<u>Phocoenoides</u> <u>dalli</u>) are incidentally taken in high seas salmon and squid driftnet fisheries (Jones 1984; Jones 1988). Dall's porpoise and harbor porpoise (<u>Phocoena</u> <u>phocoena</u>) are also caught in coastal salmon gillnet fisheries in Alaska (Maktkin and Fay 1980) and Washington. Harbor porpoise are incidentally taken in gillnets off California (DeMaster et al. 1985; Diamond and Hanan 1986; Hanan et al. 1986). Bottlenose dolphins (<u>Tursiops sp.</u>) and spinner dolphins (<u>Stenella</u> <u>longirostris</u>) are caught by gillnets in the northern Australian seas (Harwood et al. 1984). Thousands of small cetaceans die annually in coastal driftnets off Sri Lanka (Leatherwood and Alling 1985). These references are but a few examples of the globally pervasive problem of incidental take of small cetaceans by gillnets. If gillnet fisheries are to continue to be used in cetacean habitats, methods to reduce or eliminate entanglement are needed.

Research in the entanglement problem has been centered on learning about the acoustics of dolphins, determining how well dolphins can recognize nets (visually or acoustically including echolocation), and studying how dolphins behave around net enclosures. Awbrey et al. (1979) studied the interaction of the Dall's porpoise with salmon driftnets and measured echolocation signals having peak frequencies between 120-160 kHz. Hatakeyama et al. (1986) conducted a sonar detection experiment with a beluga whale in a tank and found that the whale's 50% detection threshold range for a salmon gillnet was about 5.5 m. The animal used relatively low amplitude clicks (182-189 dB re 1 μPa) which were much lower than the 198-202 dB recorded by Au et al. (1985) in San

Diego Bay, and up to 225 dB recorded in Kaneohe Bay (Au et al. 1987). Soeda et al. (1986) also used a beluga in a vision experiment and found that the animal could visually recognize fishing nets underwater. Ishii et al. (1986) conducted a field study to determine how acoustic stimuli such as simulated echolocation clicks and killer whale (<u>Orcinus</u> <u>orca</u>) sound emissions affected the behavior of the Dall's porpoise. The results were inconclusive since it was difficult to approach the porpoises without causing them to scatter. Hatakeyama et al. (1987) captured a Dall's porpoise and monitored its acoustic emissions and response to different acoustic stimuli. The acoustic emissions of the Commerson's dolphin which has an acoustic signal similar to the Dall's porpoise (Evans et al. 1988) were monitored and studied by Hatakeyma et al. (1988b) in an oceanarium tank. Gillnets have been introduced into tanks containing bottlenose dolphins (Hatakeyama and Ishii 1987) and a harbor porpoise (Hatakeyama et al. 1988a) and the animal's echolocation signals were monitored as they swam around the nets. The bottlenose dolphins easily detected the gillnet. The harbor porpoise detected the gillnet only when it was about 1 to 2 m from the net. Pence (1986) performed pulsed sinewave reflectivity measurement on a gillnet and suggested ways to increase the reflectivity of nets. Despite these studies, we still do not know how far dolphins can detect gillnets by echolocation and seem far from solving the incidental catch problem.

The objectives of this study were to measure the acoustic reflectivity of a variety of nets and associated gears with broadband simulated dolphin echolocation signals, and to predict the maximum biosonar detection ranges of nets and associated gear using the Atlantic bottlenose dolphin as the model. The use of <u>Tursiops</u> <u>truncatus</u> as a model come from the lack of data concerning

other species. Reliable target detection and related acoustic data that can be used to calculate net detection ranges only exist for a few cetacean species such as Tursiops truncatus (Au 1988a) and Pseudorca crassidens (Thomas and Turl 1990). Unfortunately, some of the phocoenids such as the Dall's porpoise do not seem to adapt well to captivity and may be difficult to train and use in any controlled experiment (Ridgway 1966). This study should be applicable to any dolphin capable of echolocation, however, special emphasis will be placed on the Dall's porpoise principally because they are incidentally taken by several high seas and coastal gillnet fisheries.

## II. TARGET STRENGTH MEASUREMENTS

### Procedure

Target strength measurements were performed at the Naval Ocean Systems Center - Hawaii Laboratory test pool using a monostatic echo measurement system that transmitted a broadband dolphin-like echolocation signal (Au and Synder 1980). The waveform and frequency spectrum of the simulated dolphin echolocation signal used in the target strength measurements are shown in Fig. 1. The incident signal had a peak frequency (frequency of maximum energy) of 122 kHz and a 3-dB bandwidth of 37 kHz. It was generated by driving a planar transducer, with an exponentially decaying four-cycle sine wave pulse. Echoes were monitored and digitized using a Data Precision Data-6000A interfaced with a Compaq Portable 386 PC. The Data-6000A performed a 16-bit analog-to-digital conversion at a 1 mHz sample rate, and the echo data were transferred to the PC and stored on a floppy disk.

The measurement geometry is depicted in Fig. 2, with the transducer submerged to a depth of 1.7 m and the distance between the target and the

transducer fixed at approximately 2.4 m. The transducer had a 3-dB transmit and receive beam width of approximately $8^{o}$ in the horizontal plane and $13^{o}$ in the vertical plane. Therefore, the effective area covered by the transducer's beam was rectangular in shape, 0.34 m in the horizontal plane and 0.55 m in the vertical plane. The incidence angle of the acoustic beam was measured with respect to a perpendicular projection from the plane of the net. Therefore at $0^{o}$ incidence angle the transducer beam was perpendicular to the plane of the net. However, the nets were laid out with a minimum of tension applied so that their shapes were not rigid but resembled wavy curtains.

There are several ways in which target strength can be defined when dealing with short broadband signals such as dolphin echolocation signals. The conventional manner in defining target strength is to compare the peak-to-peak values of the incident and reflected sound pressure levels (SPL) as described in Eq. 1

$$TS_{pp} = 20 \text{ Log } (SPL_r/SPL_i) \qquad (1)$$

where $SPL_r$ is the SPL of the target echo referenced to a distance 1 m from the target, and $SPL_i$ is the SPL of the incident signal at the location of the target. However, if an energy detection scheme is used to process the echoes then the target strength needs to be defined in terms of the ratio of the incident and reflected energy flux density

$$TS_e = 10 \text{ Log } (E_r/E_i) \qquad (2)$$

where $E_r$ is the energy flux density of the echo referenced to 1 m from the target and $E_i$ is the incident energy flux density measured at the target. The energy flux density is defined as

$$E = \frac{1}{\rho c} \int_0^T p^2(t)\,dt \tag{3}$$

where p(t) is the instantaneous acoustic pressure, $\rho$ is the density and c is the speed of sound in water. Au et al. (1988) have shown that *Tursiops truncatus* process sonar echoes like an energy detector with an integration time of approximately 264 $\mu$s. Therefore, if T in Eq. 3 is larger than the integration time, then the energy flux density should be integrated only to 264 $\mu$s to give a third target strength, $TS_{tt}$, applicable to *Tursiops truncatus*. All three definitions of target strength will be given in this paper since it is not clear which would be most applicable to other dolphins.

## Fishing Equipment Investigated

Target strength measurements of two distinct categories of fishing equipment were made. The first category consisted of five different types of fishing nets used in the Alaskan waters. These nets were as follows:

1. Commercial gillnet used in the salmon mothership fishery, constructed of 0.49 mm diameter monofilament lines and configured with 10-cm mesh size (distance between adjacent parallel lines).
2. Prototype hollow core monofilament net constructed of 0.68 mm diameter hollow core monofilament configured with 12.7-cm mesh size.
3. Macah Tribal setnet used for salmon fishing, constructed of 0.97 mm diameter filament strands (three monofilament per strand) configured with 20.3-cm mesh.
4. Multifilament net constructed of 0.58 mm diameter nylon filament strands (3 nylon filaments per strand), configured with a 11.4-cm mesh size (designated as Multi A).
5. Multifilament net constructed of 0.58 mm diameter nylon filament

strands (3 nylon filaments per strand), configured with a 14.0-cm mesh size (designated as Multi B).

The second category of fishing equipment measured consisted of objects that could be attached to nets in order to increase their acoustic reflectivity. These objects included:

1. Poly Rope, 0.635 cm diameter twisted polyester rope.
2. Household light switch chain.
3. Surgical rubber tubing - .476 cm outer diameter by .318 cm inner diameter (air-filled).

These line-like objects were weighted and dangled vertically in front of the transducer.

Target Strength Results

The echo waveforms and frequency spectra of acoustic reflections from the commercial gillnet are shown in Fig. 3, for different angles of incidence. The echo waveforms are relatively complex at all angles of incidence with many highlights in the echo waveform. With such complex echo structures, target strength based on the incidence and reflected energy (Eqs. 2 and 4) will generally be higher than the target strength based on the peak-to-peak SPL. The target strength did not vary much with the incidence angle. This probably was a result of the nets being suspended like a wavy curtain which produced relatively similar echoes for different incidence angles. The other nets also had similarly complex echo structures with very little variation in target strength with incidence angle.

Target strength measurements for the nets are tabulated in Table 1. Target strength based on the energy in a 1 ms window was the highest (least negative value), followed by the target strength based on a Tursiops' 264 $\mu s$

integration time. Target strength based on the peak-to-peak values of the echoes has the lowest value (largest negative number). The standard commercial gillnet had the lowest target strength, varying between -62.4 dB and -52.6 dB, depending on the type of target strength and the angle of incident. Therefore, the standard gillnet would be the most difficult of the five nets for an echolocating dolphin to detect. The hollow monofilament net did not have an appreciably greater (approximately 7-8 dB) target strength than the standard monofilament gillnet.

The target strength of each object in the associated fishing gear category is given in Table 2. The echo waveform for each item consisted of a single reflection, resembling the incident signal, with no other highlights. Therefore the three types of target strength are the same for the associated gear. Except for the unsoaked poly rope, target strengths of all of the objects were similar, varying from -29.1 to -36.5 dB. The unsoaked poly rope had the highest target strength which may have been due to bubbles or air pockets trapped between the fibers of the rope. When the rope was left in the water for 24 hrs, the gas pockets dissipated, resulting in a lower target strength for the soaked rope. The surgical tubing samples were knotted on both ends ensuring that air would be trapped in each sample. The target strength of the associated gear was at least 20 dB greater than the standard monofilament gillnet. This means that the reflectivity of a gillnet can be increased substantially by attaching various objects to it.

Target Strength for Dall's Porpoise Signal

The applicability of target strength measurements obtained with a simulated *Tursiops truncatus* signal to the *Phocoenoides* situation will be briefly considered in this section. Very little data on the echolocation

signal of the Dall's porpoise in open waters exist. Hatakeyama and Soeda (1990) were fortunate enough to observe about 10 Dall's in the Bering Sea during extremely calm conditions. Two to four individuals repeatedly approached within ~2 m of a hydrophone suspended on the port side of the salmon research vessel. Hatakeyama and Soeda (1990) were able to record the porpoises' echolocation signals and found typical source levels of 165 - 170 dB re 1 $\mu$Pa, with peak frequencies between 135-149 kHz. These signals had peak frequencies which were 30-40 kHz higher than signals measured in tanks. The open ocean signals were also about 13 dB higher in amplitude than recordings of Dall's porpoises in tanks. However, still higher amplitude signals are probably used by these porpoises when echolocating on distant objects. Au (1980) has shown that Tursiops typically emitted much lower amplitude signals when echolocating on very close objects. Through the generosity of Dr. Hatakeyama, we were able to obtain examples of some Dall's sonar signals measured in the open seas. An example of a Dall's porpoise sonar signal is shown in Fig. 4.

The reflection of a Dall's porpoise sonar signal from the gillnet can be mathematically calculated by using the data obtained with the simulated Tursiops signal. The transfer function in frequency domain of the gillnet can be calculated by dividing the complex Fourier transform of the gillnet echo shown in Fig. 3 by the Fourier transform of the incident signal. By mathematically performing a convolution operation between the transfer function of the gillnet and the Dall's porpoise signal shown in Fig. 4, the gillnet reflection for the Dall's porpoise signal can be obtained. The gillnet echo for a Dall's porpoise sonar signal for a 0° incident angle is shown in Fig. 5. There is little difference in the target strength based on energy between the

results shown in Figs. 3 and 5. The echo structure of both echoes is equally complex with many highlights. In the frequency domain, the bandwidth of the echo obtained with the Dall's porpoise signal is narrower because of the narrower bandwidth of incident signal.

## III. PREDICTION OF BIOSONAR DETECTION RANGES OF GILLNETS

The simplest and most accurate way of predicting the detection ranges of gillnets by echolocating dolphins is to use target detection data obtained under controlled laboratory-like conditions and extrapolating the data for open ocean conditions. Unfortunately, there is very little biosonar detection data as a function of range available except for Tursiops truncatus (Au and Snyder 1980; Murchison 1980; Au 1988a) and Pseudorca crassidens (Thomas and Turl 1990). Both species have similar target detection capabilities.

The correct detection sonar performance of a Tursiops truncatus detecting a 2.54-cm and a 7.62-cm diameter sphere in Kaneohe Bay, Oahu, Hawaii, is shown in Fig. 6. Correct detection performance is defined as the percentage of trials in which the dolphin correctly detected the target when the target was present. The conventional detection threshold at 50% correct detection occurred at 73 m for the 2.54-cm diameter sphere (Murchison 1980) and at 113 m for the 7.62-cm diameter sphere (Au and Snyder 1980). In this analysis the 90% correct detection threshold will be used along with the results pertaining to the 7.62-cm sphere, which has a target strength of -28.3 dB (Au and Snyder 1980). Both performance curves are comparable if the difference in the target strength between the 2.54-cm and 7.62-cm spheres is accounted for (Au and Synder 1980). Another factor should be related to the performance curves of Fig. 6, namely the noise condition of Kaneohe Bay where the sonar detection experiment was performed. A curve of the ambient noise in Kaneohe Bay can be

found in Au et al. (1985). The noise is due primarily to the presence of one of the noisiest populations of snapping shrimp in the world (Albers 1965).

The sonar detection range for different targets in a different noise environment can be predicted by using the noise-limited form of the sonar equation. The noise-limited form of the sonar equation modified for dolphin sonar signals can be expressed in dB as (Au 1988b)

$$DT_E = SE - 2TL + TS_{tt} - (NL - DI) \tag{4}$$

where:

$DT_E$ = detection threshold

SE = source energy flux density

TL = one way transmission loss

$TS_{tt}$ = target strength based on energy within <u>Tursiops</u>' integration time window

NL = noise level

DI = receiving directivity index

The one way transmission loss can be expressed simply as the spherical spreading loss plus an absorption term,

$$TL = 20 \log R + \alpha(f_p)R \tag{5}$$

where:

R = target range in meters

$\alpha(f_p)$ = the absorption coefficient evaluated at the peak frequency of the dolphin sonar signal

Although energy flux density is used in the sonar equation, peak-to-peak sound pressure level is more commonly used in describing the levels of dolphin signals. Au (1988b) derived a simple relationship between the source energy flux density and the source level (SL) by expressing the dolphin sonar signal as

$A \cdot s(t)$, where A is the peak amplitude and $s(t)$ is the waveform function ($|s(t)| \leq 1$), so that

$$SE = SL - 6 + 10 \text{ Log } \left( \int_0^T s^2(t)\, dt \right) \qquad (6)$$

The log integral term for a typical *Tursiops* signal in Kaneohe Bay is approximately -52 dB, and for the Dall's porpoise signal shown in Fig. 4 it is -47 dB. Therefore, SE = SL - 58 dB for *Tursiops*, and SE = SL - 53 dB for *Phocoenoides dalli*. For a given peak-to-peak source level, the Dall's porpoise sonar signal (because of its longer duration) has approximately 5 dB or 3 times more energy than the signal of *Tursiops*.

The sonar equation will now be used to calculate the sonar detection range for *Tursiops* in a different location than Kaneohe Bay and for a different target. Let the subscript KB refer to the data obtained in Kaneohe Bay (Fig. 6) and let subscript DL refer to a different location and target. The predicted detection range can be calculated by applying the sonar equation to two different locations, assuming the same detection threshold and directivity index, so that

$$2TL_{DL} = (SL_{DL} - SL_{KB}) + ([TS_{tt}]_{DL} - [TS_{tt}]_{KB}) - (NL_{DL} - NL_{KB}) + 2TL_{KB} \qquad (7)$$

From Fig. 6, the 90% correct detection performance level occurred at a range of 99 m for the 7.62-cm spherical target. The ambient noise in Kaneohe Bay at a frequency of 120 kHz (typical peak frequency for *Tursiops*) is approximately 55 dB (Au 1988a) and the average peak-to-peak source level was approximately 222 dB re 1 $\mu$Pa. Substituting these numbers into Eq. 7 and using Eq. 5 to calculate the transmission loss, we get

$$40 \log R_{DL} + 2\alpha(f_p)R_{DL} = (SL_{DL} - 222) + ([TS_{tt}]_{DL} + 28.3) - (NL_{DL} - 55) + 88.5 \tag{8}$$

An absorption coefficient of 0.044 dB/m (assuming a 24° C water temperatur was used for Kaneohe Bay.

We will assume a deep water (greater than 50 m) situation so that the typical deep water noise spectral density is applicable. An absorption coefficient of 0.03 dB/m for a water temperature of 5°C will also be assumed. For sea state conditions between 0 and 3, the noise at 120 kHz is at the thermal limit and is equal to 27 dB re 1 $\mu Pa^2/Hz$ (Albers 1965). The noise then increases linearly to 33 dB for sea state 6. From Table 1, the target strength, $TS_{tt}$, for the gillnet averaged across incident angles of 0 to 45°, is approximately -57 dB, and from Table 2, the target strength of the associated gear varied between -26 and -37 dB.

The 90% probability of detection range for Tursiops truncatus emitting signals with peak-to-peak source levels comparable to the Dall's porpoise is shown in Fig. 7 as a function of the sea state and for different peak-to-peak source levels. The 90% probability of detection range represents the maximum range at which a Tursiops should be able to detect a target 90% of the time. The curves indicate that if a Dall's porpoise has target detection sensitivity comparable to Tursiops and emitted signals with source levels of 170 dB, it should be able to detect a gillnet at a range of at least 7.6 m in sea state 0 - 3 and at 5.5 m in sea state 6. For a source level of 180 dB the detection ranges would increase to at least 14 m in sea state 0 - 3 and 9.6 m in sea state 6. For a given peak-to-peak source level, a Dall's porpoise may be able to detect a gillnet at roughly 20 to 30% longer ranges than Tursiops, because its longer signals contain approximately 5 dB more energy. This factor was

not considered in adapting the results shown in Fig. 7 to the Dall's porpoise. Nevertheless, these detection ranges are sufficiently long for a swimming echolocating dolphin to detect a gillnet in time to avoid the net. The results shown in Fig. 7 also indicate that the detection range of a gillnet can be increased substantially if the different associated items were tied to the net.

## IV DISCUSSION AND CONCLUSIONS

The target strength measurements and sonar detection range calculations indicate that echolocating Tursiops and other odontocetes including Dall's porpoises should be able to detect gillnets at long enough ranges to avoid entanglement. This conclusion is supported by field observations reported by Hatakeyama and Soeda (1990). They once observed Dall's porpoises around a salmon research vessel in the Bering Sea as gillnets were being retrieved. They saw two Dall's porpoises out of three in a group dive and pass under the gillnet and reappeared on the other side. However, the third one got entangled in the net. They also twice observed a Dall's porpoise passing through a 1.5 m wide, 1.0 m high hole of a damaged gillnet without changing their swimming speed of 3 to 4 m/s. On another occasion they discovered a school of Dall's porpoises along the coastal area of east Hokkaido and set a gillnet (1,300 m long, 6 m deep). The porpoises were chased toward the gillnets with 4 boats. Upon approaching the net the porpoises changed their swimming direction and swam along the net or dived and passed under the net. In one case, two porpoises out of a group of three dived suddenly when they were about 4 to 5 m from the net and surfaced about 10 m on the other side. The third animal swam into the net and broke through it. Hatakeyama and Soeda (1990) concluded that Dall's porpoise can detect gillnets by echolocation and can also distin-

guish holes within nets. If a Dall's porpoise is swimming at a higher speed than 3-5 m/s, it may not detect a net soon enough to avoid it, but its chances of bursting through the net should also increase with swim speed.

Since this analysis a field observations indicate that echolocating dolphins should be able to detect gillnets at sufficient ranges to avoid them, why then do they still get entangled? There are probably many answers to this question including the following possibilities: 1) Dolphins may not echolocate while transiting a body of water. In the vast expanse of the ocean, there seems to be little need for dolphins to echolocate except to detect prey. However, very little is known on how odontocetes utilize their echolocation capabilities in the wild. 2) The problem may be in the difference between detecting and perceiving an obstacle. Although the nets are detectable, the echoes will be relatively weak, and a dolphin may not perceive the net as an obstacle but as a penetrable entity. Dolphins probably encounter sources of volume reverberation that are penetrable, such as the deep scattering layer, and may not perceive gillnets as harmful obstacles. In the vast expanse of the ocean, the concept of a barrier is probably very foreign to an animal. Adding more acoustically reflective items such as poly rope, light switch chains or lengths of surgical rubber tubing on a net may help to make a net seem more impenetrable. However, Hembree and Harwood (1987) have experimented with the use of metallic bead chain on gillnets and found them ineffective in reducing the incidental take of Tursiops truncatus and Stenella longirostris in Australian waters. 3) In some circumstances Dall's porpoises and other odontocetes may be feeding on prey that inhabit the same general location where salmo. and other fishermen ty, .cally set driftnets (Ellis 1989). Treacy and Crawford (1979) noted that Dall's porpoises fed on deep-sea

fish species that approached the surface at night. Salmon gillnets usually extend from the surface to depths of 8 to 10 m. Therefore, the porpoises may be too distracted by prey to notice the presence of gillnets or may not be able to distinguish between the sonar reflections from prey and gillnets. 4) The presence of entangled fish and aggregation of free swimming fish in the immediate vicinity of a gillnet may prevent dolphins from acoustically sensing the presence of the net. The sonar returns from free swimming and entangled fish may mask the presence of gillnets, since the echoes from the nets will be much smaller than echoes from the fishes. For example, from the expression of fish target strength given by Love (1971), a 40-cm long salmon will have a target strength (frequency of 120 kHz) between -26 and -33 dB, considerably greater than the target strength of a gillnet. 5) The disturbances caused by entangled, struggling fish may actually attract dolphins to a net. As dolphins approach a net to investigate the cause of the commotion, the entangled fish may also distract them from sensing the presence of the gillnet.

In searching for viable solutions to the incidental gillnet capture problem, we should perhaps concentrate in areas other than the animal's sonar detection capabilities. Although only thoughtful speculations on why dolphins seem not to detect gillnets are presented here, some of these speculations should be seriously considered in future research. There is a need to obtain better understanding of the dynamics involved with the incidental catch problem. Why do dolphins swim close to gillnets? How do they typically get entangled? What percentage of dolphins swimming towards a gillnet actually become entangled? What is the role of fish and other marine life already entangled or entrapped by gillnets in attracting porpoises to the nets? Part

of the dynamics may involve the presence of large quantity of entangled marine life which attracts animals to gillnets, and there may not be any way to discourage dolphins and porpoises from avoiding these nets.

Table 1. Target strength of various commercial and experimental gillnets.

| Net Type | Incidence Angle | $TS_{pp}$(dB) | $TE_e$(dB) | $TS_{tt}$(dB) |
|---|---|---|---|---|
| Commercial Gillnet | $0^o$ | -58.8 | -52.6 | -54.0 |
| | $15^o$ | -62.4 | -55.2 | -58.6 |
| | $30^o$ | -60.2 | -54.5 | -57.3 |
| | $45^o$ | -60.2 | -53.7 | -58.3 |
| Hollow Monofilament | $0^o$ | -50.2 | -45.9 | -46.4 |
| | $15^o$ | -52.9 | -48.8 | -49.4 |
| | $30^o$ | -51.5 | -48.2 | -48.8 |
| | $45^o$ | -53.8 | -49.0 | -54.0 |
| Macah Tribal Set | $0^o$ | -36.7 | -36.2 | -36.2 |
| | $15^o$ | -49.3 | -43.6 | -43.7 |
| | $30^o$ | -55.8 | -47.7 | -49.4 |
| | $45^o$ | -55.8 | -47.7 | -49.4 |
| Multifilament A | $0^o$ | -42.4 | -38.9 | -39.0 |
| Multifilament B | $0^o$ | -50.4 | -44.8 | -45.0 |

Table 2. Target strength of associated fishing gear

| Material | Target Strength (dB) |
|---|---|
| Poly Rope (unsoaked) | -25.8 |
| Poly Rope (soaked 24 hrs) | -33.0 |
| Light Switch Chain | -36.5 |
| Surgical Rubber Tubing | |
| 15.2 - cm length | -32.1 |
| 30.5 - cm length | -30.9 |
| 45.7 - cm length | -29.3 |
| greater than 50 cm length | -29.1 |

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## FIGURE CAPTIONS

Fig. 1. Simulated dolphin echolocation signal used in the target strength measurements. The top curve is the signal waveform and the bottom curve is its frequency spectrum.

Fig. 2. Geometry used in measuring the target strength of nets and associated gear.

Fig. 3 Echo waveform and frequency spectra of acoustic reflections from the commercial monofilament gillnet for angles of incident of 0, 15, 30 and $45^{o}$. The target strength based of peak-to-peak ampli tude ($TS_{pp}$), energy in a 1 ms window ($TS_e$) and energy in the 264 $\mu$s integration window of Tursiops ($TS_{tt}$) are also included.

Fig. 4. Example of a Dall's porpoise sonar signals measured in the Bering Sea ourtesy of Dr. Y. Hatakeyama). The top curve is the signal waveform and the bottom curve is its frequency spectrum.

Fig. 5. Calculated reflection from the gillnet for the Dall's porpoise signal shown in Fig. 4. The incident angle is normal to the net.

Fig. 6. Target detection capability as a function of range for a Tursiops truncatus in Kaneohe Bay, Oahu, Hawaii. The long dash line is for the traditional 50% correct detection threshold and the sh rt dash line is for the 90% correct detection threshold used in this study (from Au, 1988a).

Fig. 7. Predicted biosonar detection of a gillnet and associated gear by a Tursiops truncatus as a function of sea state condition for different peak-to-peak source levels. A Dall's porpoise should have longer detection ranges since its signal has 5 dB more energy than a Tursiop's signal for the same source level.

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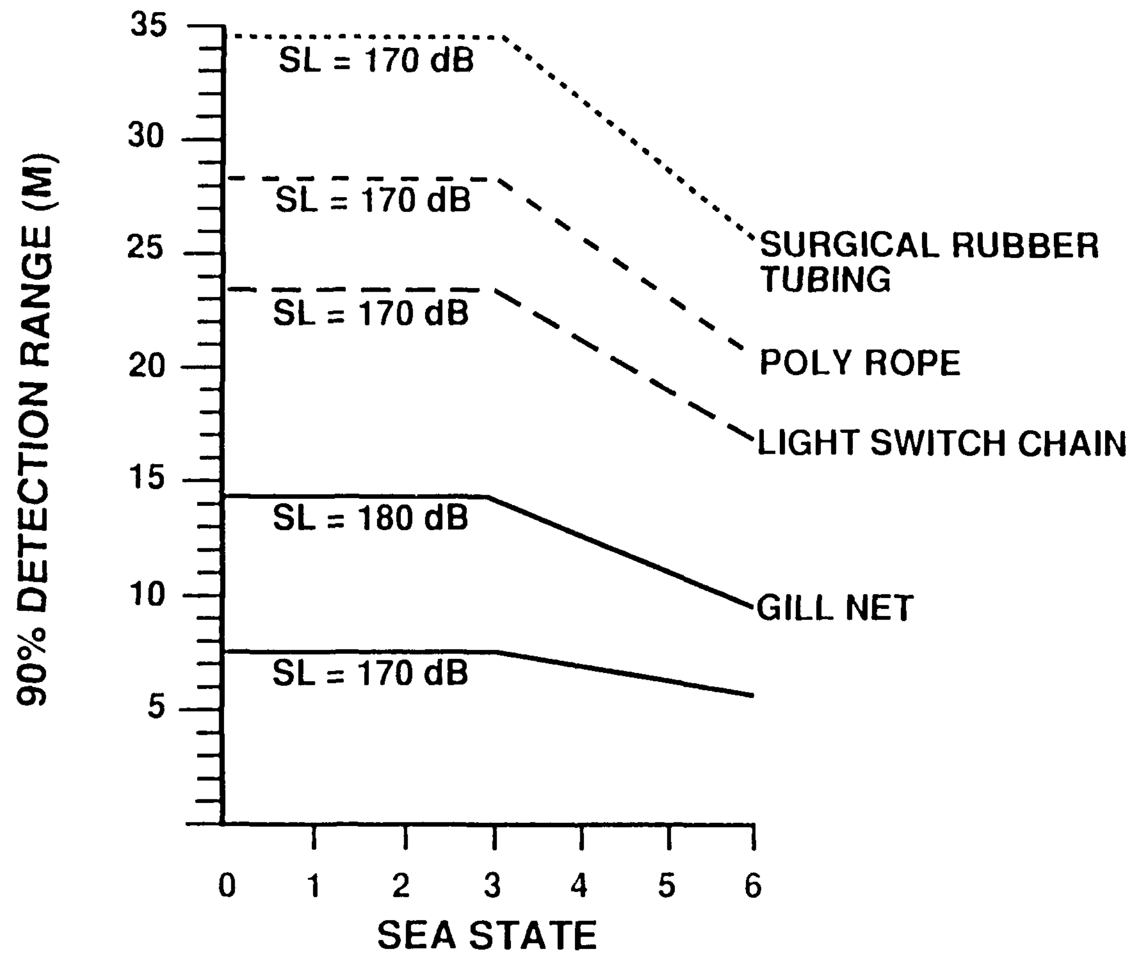
90% DETECTION RANGE (M)
35
30
25
20
15
10
5
SL = 170 dB
SL = 170 dB
SL = 170 dB
SL = 180 dB
SL = 170 dB
SURGICAL RUBBER TUBING
POLY ROPE
LIGHT SWITCH CHAIN
GILL NET
0
1
2
3
4
5
6
SEA STATE

Fig. 7

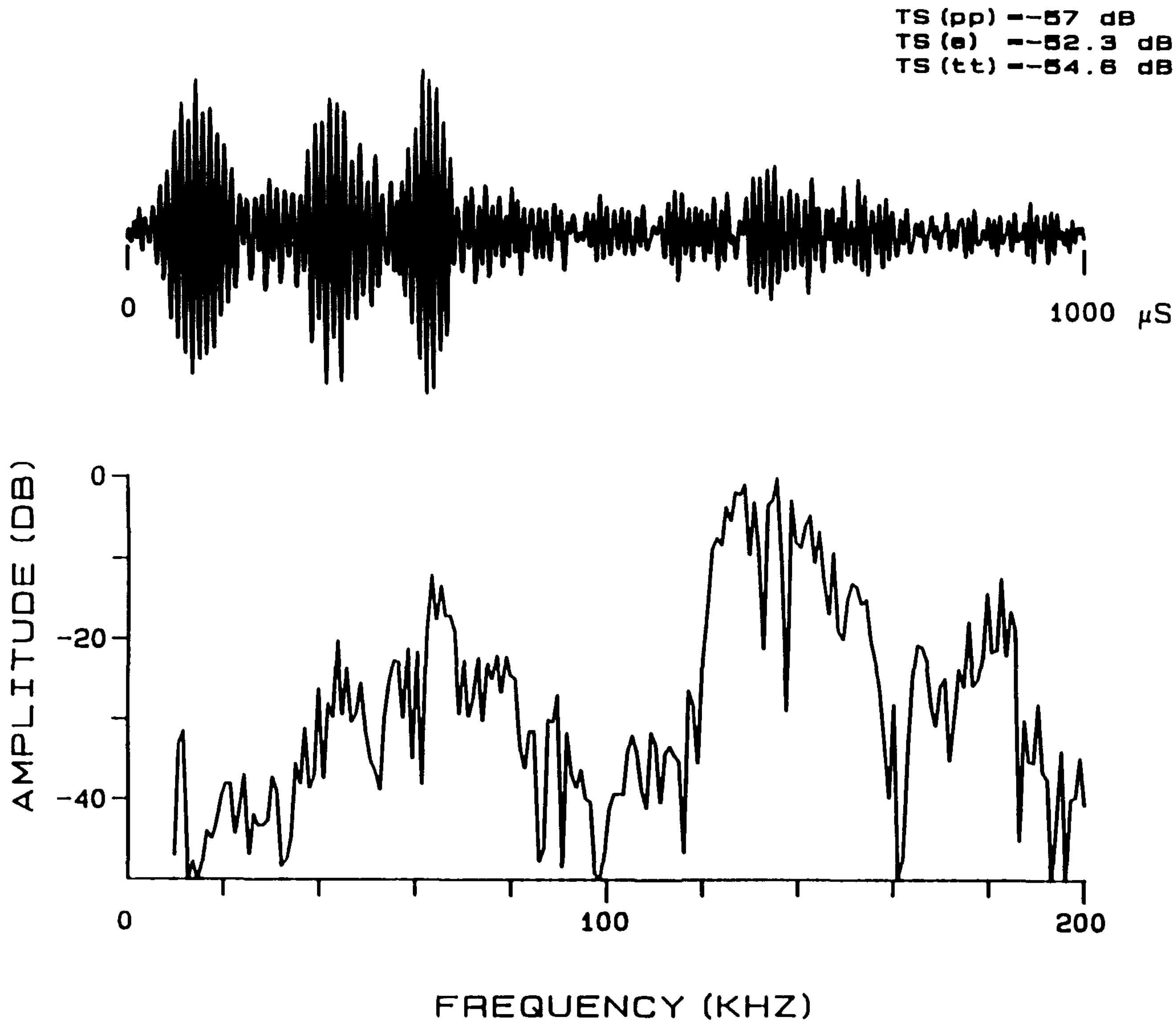
TS (pp) =-57 dB
TS (e) =-52.3 dB
TS (tt) =-54.6 dB
0
1000 μS
AMPLITUDE (DB)
0
-20
-40
0
100
200
FREQUENCY (KHZ)

Fig. 5

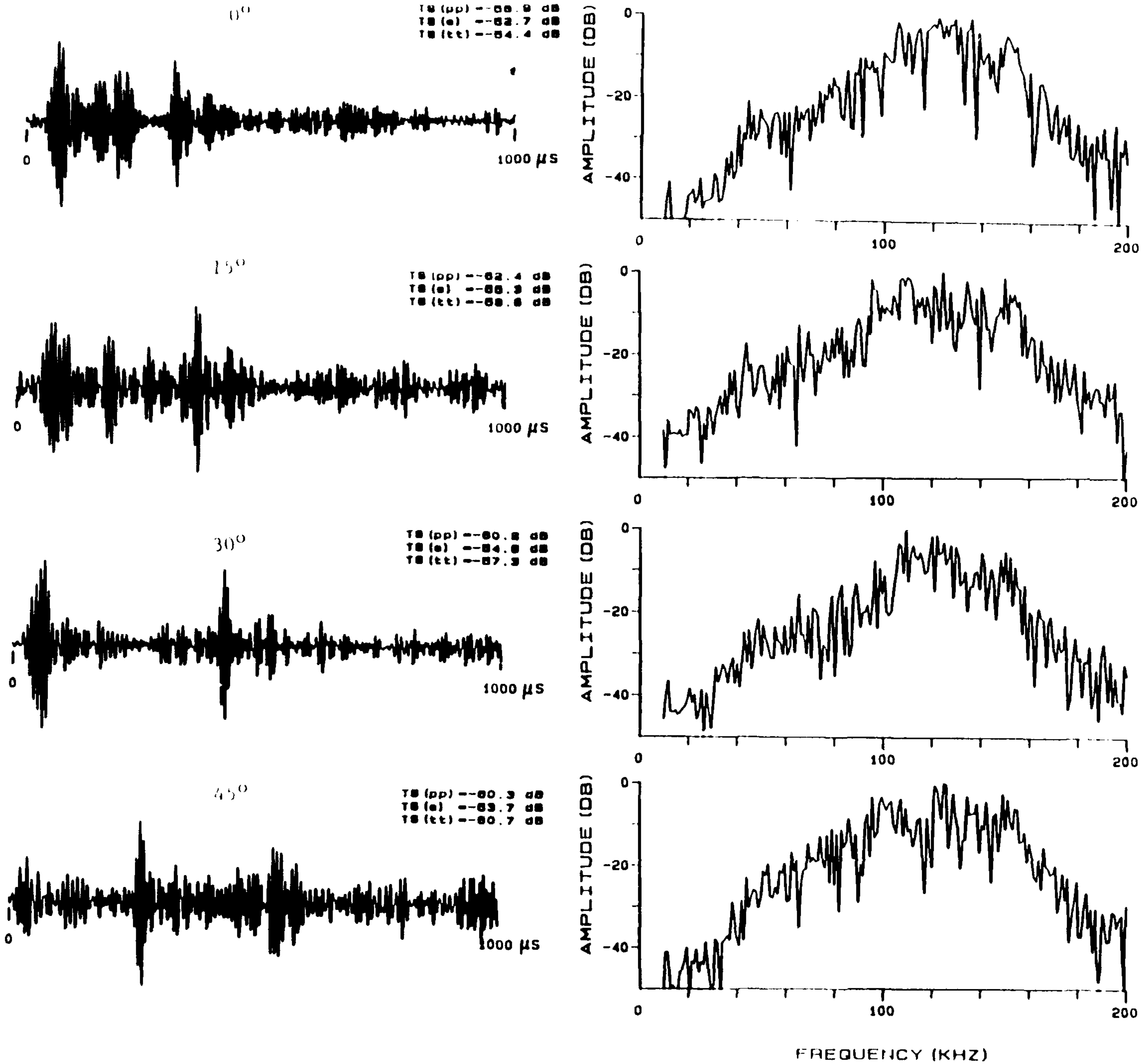
0°
TS (pp) --58.9 dB
TS (e) --62.7 dB
TS (tt) --64.4 dB
15°
TS (pp) --62.4 dB
TS (e) --66.3 dB
TS (tt) --68.6 dB
30°
TS (pp) --60.8 dB
TS (e) --64.8 dB
TS (tt) --67.3 dB
45°
TS (pp) --60.3 dB
TS (e) --63.7 dB
TS (tt) --60.7 dB
0
1000 μS
AMPLITUDE (DB)
0
-20
-40
100
200
FREQUENCY (KHZ)

Fig. 3

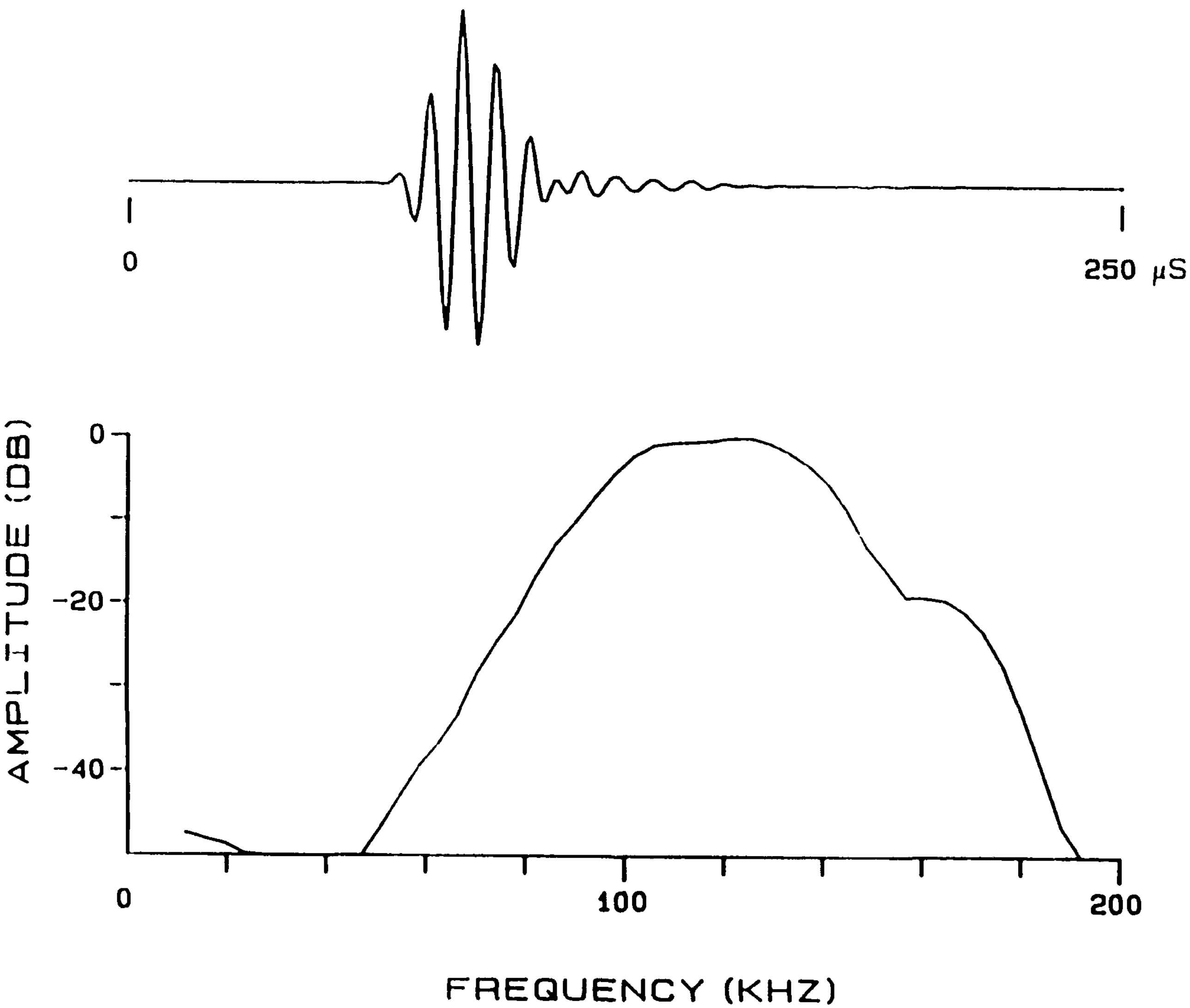


Fig. 1